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Title:

METHOD AND APPARATUS FOR STABILIZING LASER WAVELENGTH

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METHOD AND APPARATUS FOR STABILIZING
LASER WAVELENGTH

FIELD OF THE INVENTION

This invention relates to laser wavelength stabilization and, more specifically, to a method and apparatus for stabilizing laser wavelength utilizing a relatively low selectivity optical filter located in a reference path of a multi-path wavelength control system.

DISCUSSION OF THE RELATED ART

An optical wavelength division multiplex (WDM) system may be used to transmit an increased quantity of information as compared to a single optical channel system. A WDM system, however, requires a stabilized light source. Stabilization may be needed to transmit laser lights of multiple wavelengths within a relatively narrow wavelength band, for example, at intervals of 1 nm or less. Moreover, in optical information processing or optical measurement, the wavelength stabilization of the laser light source is an important parameter for enhancing the density of information and improving the precision of measurement.

The emission wavelength of a laser light source can be stabilized

by employing an optical filter having a predetermined wavelength

transmission characteristic, and by detecting an error from the desired

emission wavelength. A control signal, based on the emission wavelength

error, is fed back to the laser light source for compensation. It is known,

for example, to stabilize the emission wavelength of a laser light source by

using a multi-layer interference optical filter or a Fabry-Perot (FP) etalon.

An FP etalon may be constructed for example as a multi-layer

single cavity filter type, where an all-dielectric mirror/spacer/mirror

structure is deposited on a glass substrate. Alternatively, a solid etalon type

may be used, in which mirrors are deposited on both sides of a glass spacer

plate. Whichever implementation is used, the intensity of the beam that is

allowed through the etalon is a function of the wavelength of the beam

incident upon it. This principal is illustrated in Figure 1 to aid in the

understanding of the present invention.

Etalon 100 is a quartz disk having flat opposed parallel surfaces

103, 105 separated by a distance "d". In Figure 1, as light beam 107

passes through the front surface 105 of the etalon 100, a reflected portion

107' is reflected back toward the back surface 103. The reflected beam

107' is itself reflected at the back surface 103 to form another reflection beam 107" which passes through the front surface 105.

Multiple reflections continue and if the distance d is equal to a half wavelength, or a multiple thereof, of the beam 107, then all reflections passing through the front surface 105 will be in phase with the original beam 107. This reinforces the transmitted beam such that maximum intensity for that particular wavelength is transmitted, with the intensity decreasing for longer and shorter wavelengths. (Figure 1 illustrates a situation where a laser light beam is coincident (or parallel) with the optical axis of the etalon 100. Although the reflection beams 107', 107" are shown displaced from one another in Figure 1, they actually may be all on the same optical axis.)

An FP etalon, like other optical filters, is periodic (multi-valued). It must either possess a certain selectivity to meet the stability specifications or possess a certain thickness to allow practical handling during manufacture. In addition, it is desirable but not necessary to have the periodicity of the FP etalon agree with the International Telecommunications Union (ITU) which is now set at $\Delta f = 100$ GHz but may be set at 50 GHz or less in the future. The periodicity or multi-valued

nature of the FP etalon can be a problem since it is difficult to determine which cycle corresponds to the desired operating point.

Hence, what is needed is a method to avoid the uncertainty associated with the periodic nature of high selectivity FP etalons or other periodic filters. There is a need in the art for an improved wavelength stabilization system that employs one or more such high selectivity filters.

SUMMARY OF THE INVENTION

A method and apparatus for laser wavelength stabilization is disclosed where a low selectivity reference filter is located in a reference path of a laser beam, and a multi-valued control filter is located in a control path. The reference filter, with a periodicity greater than the control filter, is used together with a lookup table to resolve the uncertainty associated with the control filter, and then the control filter is used to lock the laser source on the desired wavelength. When a change request to another wavelength is received, the reference filter lookup table is consulted to determine what parameters are associated with that wavelength and the operation is then set within the desired cycle or period of the control filter.

The above advantages and features of the invention will be more

clearly understood from the following detailed description which is

provided in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 schematically illustrates the operation of an FP etalon

(an example of a multi-valued optical filter);

Figure 2 is an illustration of a wavelength stabilized laser system

constructed according to the present invention;

Figure 3 illustrates a method of utilizing a reference period

which is twice that of the control period;

Figure 4 illustrates a method of utilizing a reference period

which is quadruple that of the control period; and

Figure 5 illustrates another method of utilizing a reference

period which is twice that of the control period.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Preferred embodiments of the present invention are illustrated in

Figures 2-5. Other embodiments may be utilized and structural changes

may be made without departing from the spirit or scope of the present

invention. Although the invention is described with reference to a single

reference filter, the invention is also applicable to laser systems that have

more than one reference filter. Also, although the reference filter may be

5   an integral part of the laser system, the invention is also applicable to lasers

having a separate reference filter. Like items are referred to by like

reference numerals throughout the drawings.

          Figure 2 is a schematic illustration of a laser system 9. The

system 9 has a laser medium 1 and a light resonator 11. The light

10   resonator 11 includes a high reflection mirror 2 and an incomplete

reflection mirror 3. The light generated by the medium 1 is amplified

while being reflected within the resonator 11 numerous times before

exiting as laser beam 6. The illustrated laser system 9 also has a reference

filter 5, a control filter 4, beam splitters 25a, 25b, a wavelength monitor

15   system 7, a control system 8, and a servo system 10 for controlling the laser

medium 1. If the laser medium 1 is a DBR laser, it can be operated by the

application of tuning currents. The laser system 9 may be connected by

optical fiber 14 (or some other waveguide) to receiver 16. The receiver 16

may include a photodiode, for example.

Reference filter 5 is preferably an FP etalon. Reference filter 5 has a lower selectivity than the control filter 4. Selectivity is defined herein as Δ transmission/Δ wavelength. Also, reference filter 5 is fabricated to have a periodicity greater than that of the control filter 4. Periodicity is defined herein as the wavelength range between consecutive maximum intensity peaks and is related to the free spectral range (FSR).

For a given wavelength range, a multiple number of maximum peaks associated with the transmission through the control filter 4 is observed for every maximum peak associated with the transmission through reference filter 5. The transmission through reference filter 5 may be utilized to determine the desired operating point cycle of the control filter 4, as will be discussed further below.

Referring still to Figure 2, the wavelength of light on reference path 12a (i.e., the wavelength of the beam that is reflected by the second beam splitter 25b) is approximately measured (as a function of its intensity) by wavelength monitor system 7. This measured value is then input into control system 8. Control system 8 may contain data (the so called "look-up table") corresponding to the various optical characteristics of the reference filter 5. The control system 8 causes a certain bias voltage and temperature (determined from the lookup table) to be applied to the laser

medium 1 by servo system 10 to bring the wavelength of the light

transmitted along reference path 12a to near a desired target. The control

filter 4, which is highly selective, is then used to bring the wavelength of

the light on control path 12b (i.e., the portion of the beam 6 reflected by

the first beam splitter 25a) to the desired value within predetermined

specifications. A feed-back loop based on the wavelength characteristics of

the light transmitted along control path 12b assures that the laser beam 6

locks onto the desired wavelength.

Figure 3 shows the reference and control responses 113, 115 of

the reference and control filters 5, 4, respectively. That is, the normalized

intensity of the light transmitted along the reference and control paths 12a,

12b is shown as a function of the wavelength of the laser beam 6. The

reference response 113 has a reference period characterized by maximum

peaks 13a, 13b. That is, the intensity of the light on reference path 12a is

at a maximum value (normalized value = 1.0) when the wavelength of the

laser beam 6 is λ_1 or λ_2.

The control response 115 has a control period characterized by

maximum peaks 15a, 15b, 15c. The intensity of the light on control path

12b is at a maximum value (normalized value = 1.0) when the wavelength

of the laser beam 6 is λ_3, λ_4 or λ_5. The period of the reference response

113 (i.e., the difference in wavelength between adjacent peaks 13a, 13b) is

greater than the period of the control response 115. In Figure 3, the

period of the control response 115 is the wavelength difference between

adjacent control response peaks 15b, 15c, such that: $\lambda_2 - \lambda_1 > \lambda_5 - \lambda_4$.

5   Assume, for example, still referring to Figure 3, that the

wavelength of the laser beam 6 immediately following a wavelength change

request is λ_6 (i.e., at a wavelength between adjacent control response peaks

15b, 15c). Assume also that the desired operating wavelength for the beam

6 is λ_5 (at the third control response peak 15c in Figure 3). In this

10   example, the operating parameters of the laser 1 (bias, temperature, etc.)

would be modified first as a function of the output of the reference filter 5

(i.e., based on the reference response 113), to move the laser beam

wavelength from λ_6 to λ_2 (i.e., to the reference response peak 13b known

to be in the vicinity of the desired wavelength λ_5). Then, feedback control

15   of the laser source 1 based on the output of the control filter 4 (i.e.,

following the control response 115) would be used to move the beam

wavelength from λ_2 to λ_5 (i.e., to the desired wavelength at the third

control response peak 15c).

    Note that, in the foregoing example, if the step of making an

20   initial, approximate laser wavelength adjustment based on the reference

response 113 were not available, then it would be difficult for the system to

distinguish between the desired wavelength λ_5 and the wavelength λ_4 at the

adjacent control response peak 15b. In other words, if the reference filter 5

were not employed, it would be difficult for the system to decide whether

to move from λ_6 to λ_5 or from λ_6 to λ_4.

In Figure 3, the reference period (λ_2 - λ_1) is twice as long as the

control period (λ_5 - λ_4). This two-to-one period relationship has the

advantage of maximizing the amplitude difference of the reference response

113 with respect to cycles of the control response 115 that are adjacent

(but not within) the desired operating point cycle. The advantage can be

illustrated as follows: In the example shown in Figure 3, the normalized

amplitude of the reference response 113 is almost 1.0 in the vicinity of the

third control response peak 15c, and is about 0.1 in the vicinity of the

adjacent, second control response peak 15b. The normalized difference in

the amplitude of the reference response 113 between the second and third

control response peaks 15b, 15c is almost 0.9 (1.0 - 0.1 = 0.9).

In the illustrated example, the second control response peak 15b

is the one that needs to be distinguished from the third control response

peak 15c. Consequently, it is advantageous to have a large amplitude

difference in the reference response 113 between the second and third

control peaks 15b, 15c, so that the reference response 113 can be used

effectively to move the wavelength of the laser beam 6 toward the

approximate desired wavelength (λ_2). If the period of the reference

response 113 were greater than twice that of the control response 115,

then, with all other parameters being equal, the normalized amplitude of

the reference response 113 would be equal to 0.1 at some point to the left

of the second control response peak 15b (in Figure 3). As a result, the

normalized amplitude of the reference response 113 would be greater than

0.1 at the second control response peak 15b, and the difference in

normalized amplitude between the second and third response peaks 15b,

15c would be less than 0.9.

The desired operating point cycle is the wavelength range within

which locking control for the laser beam 6 can be accomplished based on

the control response 115. In the system described above, the wavelength

of the laser beam 6 is first moved into the desired operating point cycle by

moving it based on the amplitude of the light transmitted through the

reference path 12a. In an alternative embodiment of the invention, the

wavelength can be moved into the desired operating point cycle by moving

it to a point where the reference and control responses 113, 115 have a

predetermined relationship. For example, the wavelength of the beam 6

could be moved into the desired operating point cycle by moving it from λ_6 to the nearest point where the reference and control responses 113, 115 are both high. Once the beam wavelength is moved into the desired operating point cycle, the control response 115 can be used to lock the wavelength of the beam 6 onto the desired wavelength λ_5.

Once the beam 6 is locked onto the desired wavelength, the characteristics of the laser medium 1 (bias, temperature, etc.) are then adjusted or maintained over time based on the control response 115 within the desired operating point cycle, until another change request is received. That is, in a preferred embodiment of the invention, the reference response 113 is only used to guide the laser beam wavelength to the desired operating point cycle of the control filter, and only the more selective control filter 4 is used then to lock and maintain the beam 6 on the desired wavelength.

In the method shown in Figure 4, the invention operates with a reference period (the wavelength difference between adjacent peaks 17) which is quadruple that of the control period (the wavelength difference between adjacent control response peaks 19a, 19b, 19c and 19d). The control system 8 compares the responses 119, 117 of control filter 4 and reference filter 5, respectively, to determine the proper operating point

cycle of the control filter 4. The characteristics of laser medium 1 are then

adjusted by the servo system 10 for operating conditions as required (i.e.

adjusted for bias, temperature, etc.) based on the wavelength characteristics

of the light transmitted along the control path 12b.

5   Figure 5 shows another way in which the present invention can

operate with a reference period which is twice that of the control period.

The maximum peaks of the reference response 121 are designated by

reference numerals 21a, 21b. The maximum peaks (wavelengths of

greatest transmission intensity) of the control response 123 are designated

10   by reference numerals 23a, 23b, 23c and 23d. In this embodiment, the

signs of the slopes of the reference response 121 can be used to

discriminate between desired and undesired wavelengths. For example, the

positive slope of the reference response 121 at a first wavelength λ_{10} can be

used to distinguish the first wavelength λ_{10} from second and third

15   wavelengths λ_{11}, λ_{12} which have negative slopes.

In this manner, if the desired operating wavelength is at the third

peak 23c of the control response 123, then the system can determine that

the first wavelength λ_{10} is in the vicinity of the desired wavelength and the

second and third wavelengths λ_{11}, λ_{12} are not near the desired wavelength.

20   That is, the system can determine that the first wavelength λ_{10} is in the

desired operating point cycle of the control filter whereas the second and third wavelengths λ_{11}, λ_{12} are not in the desired operating point cycle, even though the amplitudes of the first, second and third wavelengths λ_{10}-λ_{12} are all about the same.

If the desired operating point cycle happens to fall near a maxima or minima of the reference filter 5 (near where its sign changes), then two reference filters with slightly different characteristics may be employed with the appropriate one chosen. The measured values are input into control system 8 which compares the slopes of the reference response 121 to determine the proper operating point cycle of the control filter 4. The characteristics of the laser medium 1 are then adjusted by the servo system 10 for operating conditions as required (i.e. adjusted for bias, temperature, etc.) based on the wavelength transmission characteristics of the control filter 4, as if the reference filter 5 were not present.

Hence, highly selective laser wavelength stabilization may be achieved by a system that has a low selectivity reference filter 5 located in a reference path 12a. The low selectivity reference filter 5, with a periodicity greater than the control filter 4, is used together with a lookup table for the reference filter 5 to resolve the uncertainty associated with the multi-valued control filter 4. After the desired region of the control filter response is

identified, the lookup table is used to calculate a control signal to be

applied to the servo system 10 based on the control filter response. Thus,

when a change request to another wavelength is received, the reference

filter lookup table is consulted to determine what parameters are associated

with that wavelength and the operation is then set within a cycle of the

control filter 4.

Although the invention has been described above in connection

with exemplary embodiments, it is apparent that many modifications and

substitutions can be made without departing from the spirit or scope of the

invention. Accordingly, the invention is not to be considered as limited by

the foregoing description, but is only limited by the scope of the appended

claims.

What is claimed as new and desired to be protected by Letters

Patent of the United States is: